

Error Compensation Phase Extraction Algorithm Used in Phase Shifting Point Diffraction Interferometer

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Abstract: Phase-shifting point diffraction interferometer is influenced by some error sources, and the precision descends. Some kinds of testing errors due to some error sources can be eliminated by phase extraction algorithm. An error compensation phase extraction algorithm designed by the author is compared with some universal phase extraction algorithms. The simulation results illuminate that the present algorithm is much more insensitive to phase shifter linearity and nonlinearity of second order, intensity fluctuation linearity and nonlinearity of 2nd order, frequency of light source fluctuation linearity and nonlinearity of 2nd order than the other two algorithms. The results also illuminate that the error compensation phase extraction algorithm have the advantage over other universal algorithms in eliminating the phase-shifting noise, intensity noise, frequency noise, vibration, temperature change, humidity change and pressure change. We have developed a point diffraction interferometer with phase-shifting technique to measure optical surface figure. A spherical concave mirror was tested with this interferometer. The error compensation phase extraction algorithm was applied during measurement. The measurement repeatability comes out better than 0.1 nm RMS and validates the simulation well.

Key words: phase-shifting point diffraction interferometer; error compensation; phase shifter error; light source error; vibration; repeatability;

1 Introduction

Exterme Ultraviolet Lithography (EUVL) projection objective extremely harsh

aberration requirement take an unprecedented challenge to optical design, optical fabrication, optical testing and system Integrated alignment^[1~5]. In order to achieve EUVL projection optics fabrication, the accuracy of optical figure measurement instrument is required to reach deep-sub-nanometer.

Point diffraction interferometer (PDI) utilizes a near-ideal spherical wavefront diffracted by a pinhole as reference beam, which eliminates the disadvantage caused by reference element used in traditional interferometers, and achieves high accuracy measurement. Since 1974 Smartt and Strong proposed PDI^[6], after years of development, PDI has been successfully applied in ultra-precision surface figure measurement and system wavefront aberration measurement^[7~9].

In this manuscript, an error compensation phase extraction algorithm is introduced. Influences caused by multi error sources are analyzed. And a concave mirror was used to estimate the wavefront repeatability of PDI by using of presented algorithm.

2 Summary of PDI and Error Compensation Phase Extraction Algorithm

Figure 1 shows the sketch map of constitution of PDI. The entire interferometer is composed by illumination system, pinhole plate, imaging system and data processing system. Illumination system focuses at and irradiates the pinhole. The diameter of the pinhole is on the order of the wavelength of light source. A near-ideal spherical wavefront diffracted by pinhole divides in two beams. One of them acts as reference beam and the other acts as testing beam. The testing beam, which is reflected by the tested surface and pinhole plate surface sequentially, is relayed on the CCD camera together with reference beam. And then interference fringe pattern are collected. It should be noticed that CCD imaging sensor should be conjugated with the optical surface under test. In order to improve the accuracy of measurement, Phase-shifting method is adapted. A piezoelectricity device is employed here for moving the tested optical element for changing the phase of interferograms.

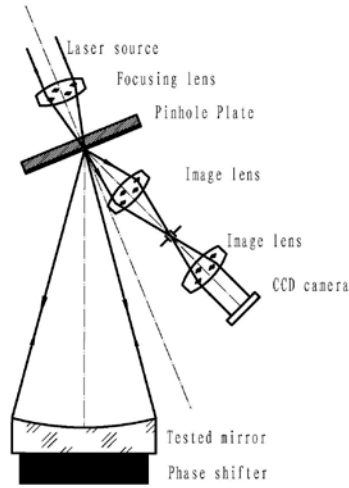


Fig.1.PSI sketch map

The intensity of phase shifting interferograms could be presented as below:

$$I_n(x, y) = a + b \cos(\Phi(x, y) + (n - 1)\delta) \quad (1)$$

a is background and b is modulation, Φ is phase which contains the information of wavefront and δ is phase space.

Multi error source of phase shifting interferometry were analyzed and then multi sets of constraint equations were obtained by using of weighted least squares algorithm. Solve these constraint equations and the weights of weighted least squares algorithm were ascertained and then the error compensation phase extraction algorithm was obtained. An error compensation phase extraction algorithm was presented below^[10].

$$\phi(x, y) = \arctan \left[\frac{\sum_{n=1}^{13} w_n \tilde{I}_n \sin(\delta_n)}{\sum_{n=1}^{13} w_n \tilde{I}_n \cos(\delta_n)} \right] \quad (2)$$

The weight mentioned in last equation is

$$\begin{aligned} w_1 &= w_{13} = 1; w_2 = w_{12} = 4 \\ w_3 &= w_{11} = 10; w_4 = w_{10} = 20 \\ w_5 &= w_9 = 31; w_6 = w_8 = 40 \\ w_7 &= 44 \end{aligned} \quad (3)$$

In section 3, multi error sources are analyzed based on presented algorithm. And the presented algorithm is compared with standard algorithms by simulation. In section 4, concave spherical mirror measurement based on PSI and presented

algorithm is introduced. In section 5, conclusions are given.

3 Errors analysis

Wavefront repeatability is the most basic evaluation of precision. The system's repeatability of measurement is defined as the difference of sequential measurements without adjusting and touching the equipment. Therefore, the repeatability is mainly influenced by the performance of devices which compose the interferometer and the environment during measurement. In this chapter, we discuss the error sources which undermine the system's repeatability and the methods to improve this property.

3.1 Phase shifting error

Phase-shifting error is caused by the imperfection of phase shifter which is one of main error sources. Phase-shifting error includes linearity phase-shifting error, nonlinearity phase-shifting error and phase-shifting noise. Previous research has confirmed that demerit caused by linearity and low-order nonlinearity phase-shifting error can be effectively decreased by adopting proper phase reversion algorithms.

Phase shifting error could be presented as below^[11]

$$\Delta\delta_n = \varepsilon_1(n-1)\delta + \varepsilon_2[(n-1)\delta]^2 \quad (4)$$

$\Delta\delta_n$ is phase shifting error of nth frame, δ is the ideal phase shifting space, ε_1 is linearity phase shifting coefficient, $\varepsilon_2, \varepsilon_3, \dots$ are nonlinearity phase shifting coefficient. The simulation of phase shifting error causing wavefront measurement error was taken, and the result refers to fig 2.

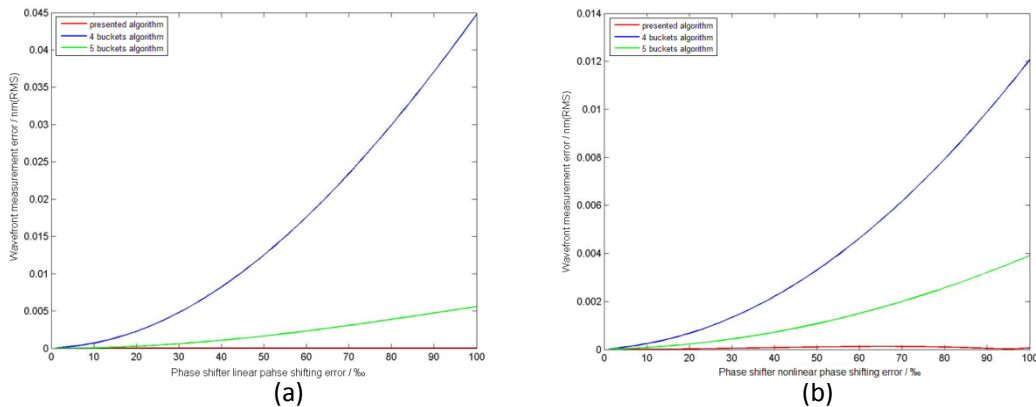


Fig.2. Wavefront measurement error due to phase-shifting error.

(a) Wavefront measurement testing error curve due to linear phase-shifting error;

(b) Wavefront measurement testing error curve due to 2nd nonlinear phase-shifting error;

3.2 Detector nonlinearity response error

The relationship between detector input and output is not completely linear, and then detector nonlinear response error is induced, which also cause phase extraction error. The simulation of detector nonlinear response error causing wavefront measurement error was taken, and the result refers to fig 3. Three kinds of algorithms could completely decrease the influence caused by detector 2nd nonlinear response and the measurement error mentioned in fig 3 is introduced by computer calculation error.

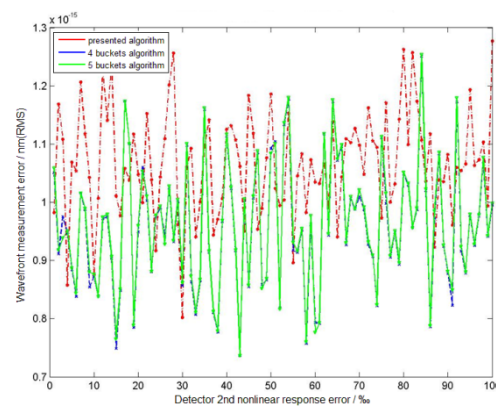


Fig.3.Wavefront measurement error due to detector 2nd nonlinear response

3.3 Instability of light source

Instability of light source is another important element of error source. It has two components: one is instability of intensity, the other one is instability of frequency. Instability of intensity influences the background and modulation of interferograms. The variety rate of background and modulation is uniform. Instability of frequency change phase of interference wavefront just like as phase-shifting error, furthermore the variety of phase at every pixel is the same. As well as phase-shifting error, that demerit caused by linearity and low-order nonlinearity instability of light source can be effectively decreased by adopting proper phase reversion algorithms.

Considering the instability of intensity, the interferogram could be presented as below equation^[11].

$$I'_n(x, y) = [1 + \varepsilon_1(n-1) + \varepsilon_2(n-1)^2 + \dots + \varepsilon_k(n-1)^k] I_n(x, y) \quad (5)$$

The simulation of intensity instability causing wavefront measurement error was taken, and the result refers to fig 4.

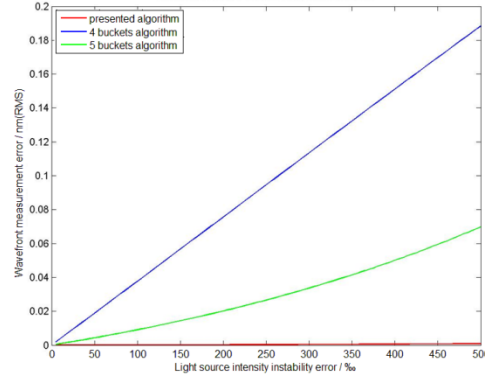


Fig.4. Wavefront measurement error due to intensity instability (0 order to 2nd).

Considering the instability of frequency, the phase change could be presented as below equation^[11].

$$\Delta\delta \approx \left[\frac{OPD \times \Delta\nu}{C} \right] \times 2\pi \quad (6)$$

This kind of phase shifting error is nearly in direct proportion to frequency change. The simulation of intensity instability causing wavefront measurement error was taken, and the result refers to fig 5.

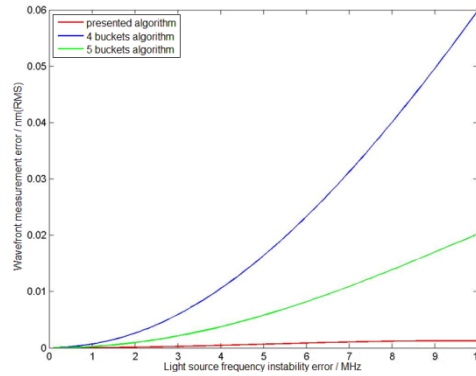


Fig.5. Wavefront measurement error due to frequency instability(0 order to 2nd)

4 wavefront repeatability measurement

Our team has developed a phase shifting point diffraction interferometer. This instrument was settled in high stable environment. The temperature stability of interference cavity is better than 0.005°C during 3 hours. A sequential measurement without adjusting was taken, and 12 wavefront results were obtained. Every result was average of 128 single result. The one of 12 measurement results, averaging result, wavefront difference, and corresponding contour are shown in fig 6. And a wavefront repeatability of 0.057nmRMS was obtained.

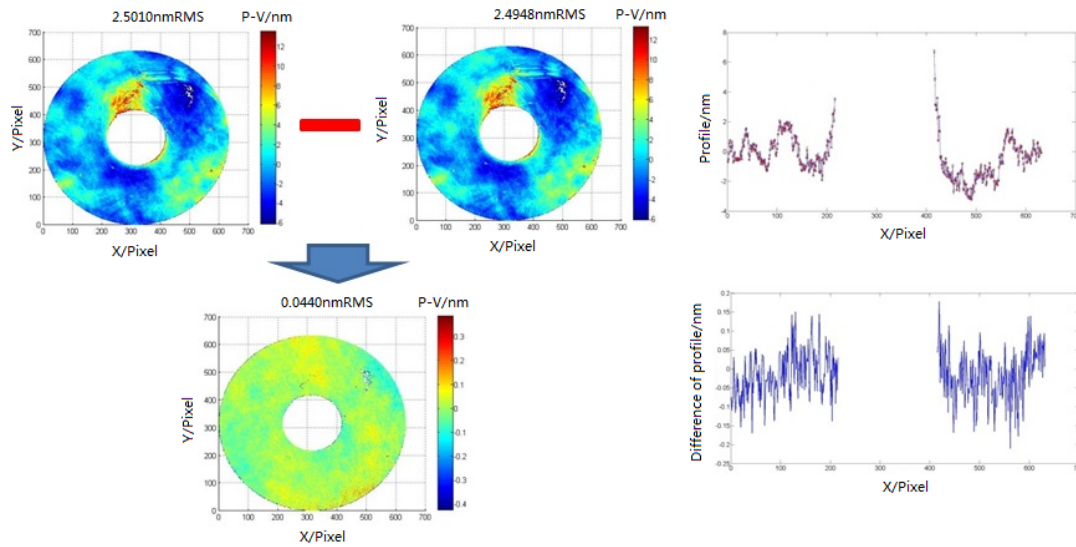


Fig.6 Wavefront Repeatability

Averaging is an effective method for enhance the wavefront repeatability. There are hardware average and software average in interferometry. The hardware average is executed in interferogram recording. The hardware average essentially is interferogram average. And the averaged interferogram should be recorded with phase shifting no movement. The software average is executed after phase extraction. In principle, the wavefront repeatability is in inverse proportion to square root of averaging times^[12]. However, the wavefront repeatability would be saturated since the long term environment would damage the precision. Fig 7 shows the relationship between wavefront repeatability and averaging times.

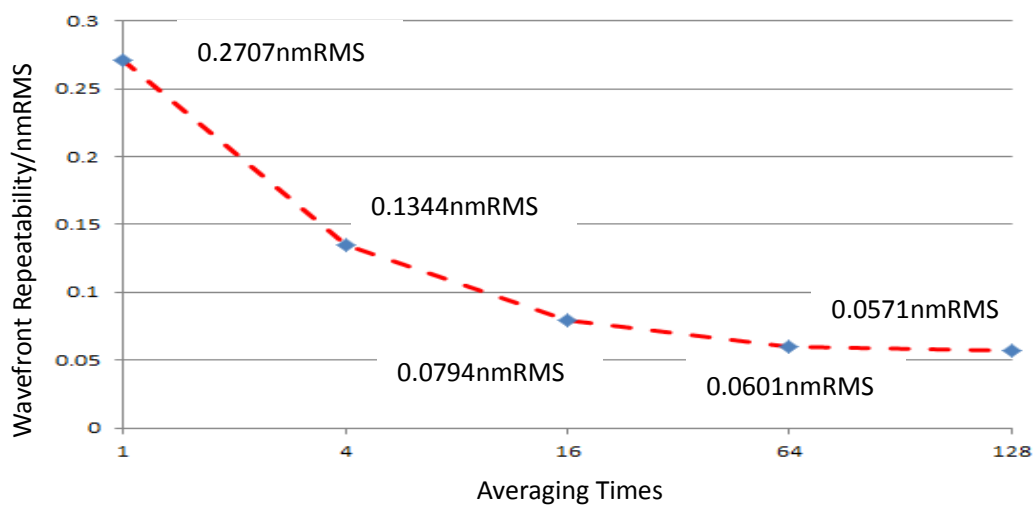


Fig.7 Wavefront repeatability improvement by Phase averaging

5 Conclusions

In this paper, an error compensation phase extraction algorithm was introduced, and the presented algorithm was compared to standard algorithms by simulation. Some kinds of error sources were analyzed. The simulation results show that presented is more insensitive to these error sources. A Wavefront repeatability measurement based on presented algorithm and PDI was done. And the wavefront repeatability of concave mirror measurement came out better than 0.1nmRMS.

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